

Teleportation with two-dimensional electron gas formed at the interface of a GaAs heterostructure

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Abstract

Inspired by the scenario by Bennett et al., a teleportation protocol of qubits formed in a two-dimensional electron gas formed at the interface of a GaAs heterostructure is presented. The teleportation is carried out using three GaAs quantum dots (say \mathcal{PP}' , \mathcal{QQ}' , \mathcal{RR}') and three electrons. The electron spin on GaAs quantum dots \mathcal{PP}' is used to encode the unknown qubit. The GaAs quantum dot \mathcal{QQ}' and \mathcal{RR}' combine to form an entangled state. Alice (the sender) performs a Bell measurement on pairs $(\mathcal{P}, \mathcal{Q})$ and $(\mathcal{P}', \mathcal{Q}')$. Depending on the outcome of the measurement, a suitable Hamiltonian for the quantum gate can be used by Bob (receiver) to transform the information based on a spin to charge-based information.

Keywords: Two-dimensional electron gas; Teleportation; Entanglement; Quantum gate.

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1 Introduction

In quantum teleportation, the whole object positioned at a point, say A cannot be teleported, but only its state with the aid of classical communication and previously shared entanglement between points A and another point, say B . This idea was expounded in a seminar paper by Bennett et al. [1]. A description of the standard teleportation protocol is as follows: The sender Alice has a source qubit, say Φ (a state of which is unknown to her) which she wants to teleport to Bob. Suppose Alice and Bob share another qubit. Then the entangled state could be represented by $|\Psi\rangle_{AB} = 1/\sqrt{2}(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B)$, where the A and B denote the quantum state of Alice and Bob respectively. Since Alice does not know the state of Φ (the laws of quantum mechanics do not permit this since she only has a single copy of $|\Psi\rangle_{A'}$ in her possession), it therefore made it impossible for her to precisely measure and specify it. Now, Alice relates the qubit in her possession with half of the EPR pair (i.e., $|\Phi^{(0)}\rangle_{A'AB} = |\Phi\rangle |\Psi\rangle_{AB}$, where $|\Phi^{(0)}\rangle_{A'AB}$ denotes the state input to the circuit) and sends the qubits through a C-NOT gate to obtain $|\Phi^{(1)}\rangle_{A'AB} =$

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$\frac{1}{\sqrt{2}} [a |0\rangle (|00\rangle + |11\rangle) + b |1\rangle (|10\rangle + |01\rangle)]$ and then through a Hadamard gate. The result of this becomes

$$|\Phi^{(2)}\rangle_{A'AB} = \frac{1}{2} [|00\rangle (a|0\rangle + b|1\rangle) + |01\rangle (a|1\rangle + b|0\rangle) + |10\rangle (a|0\rangle - b|1\rangle) + |11\rangle (a|1\rangle - b|0\rangle)]. \quad (1)$$

It then implies that every state of Alice's qubits (i.e. $a|0\rangle + b|1\rangle$, $a|1\rangle + b|0\rangle$, $a|0\rangle - b|1\rangle$, $a|1\rangle - b|0\rangle$) corresponds to a state of Bob's qubit (i.e., $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$). Once Bob gets the result of this measurement, he can reconstructs the state Φ by applying the appropriate quantum gate. As it has just been demonstrated, a quantum state can be recovered in a remote location with the aid of a maximally entangled EPR pair and two bits of classical information. On the basis of this novel idea, there has been a continuous interest in studying quantum teleportation. The literature is huge, however, the following references [2, 3, 4, 5, 6, 7, 8] give some older as well as recent studies. On a general notes, what have be teleported includes photons (already done), atoms (already done), molecules (probably soon), etc. The prerequisites for quantum teleportation are:

- A qubit that is to be teleported; this can be in a linear combination of its basis states, i.e., $|\Phi\rangle_{A'} = a|0\rangle + b|1\rangle$
- Communication channel which is capable of relaying two classical bits
- Means of generating and distributing an entangled Einstein-Podolsky-Rosen (EPR) pair of qubit between two points (say, A and B).

Moreover, the usefulness of entanglement is not restricted to teleportation alone, it also forms an imperative component in quantum cryptography and quantum information shairing. All these justify indispensability of an entanglement in quantum information processing. It is a manifestation of intrinsic non-locality in the quantum mechanic. A comprehensive understanding of behavior of entangled systems in their environs has been an investigation which is common to quantum measurement and quantum information. To the best of our knowledge, no much work on teleportation in semiconductor has so far been achieved. Nanoscale systems such as quantum dots and superconducting circuits make good candidates of standard semiconductor technology for practical quantum computers. Within this context, a quantum teleportation might be a decisive confirmation of its potentiality.

A quantum dot is a semiconductor nanostructure that incarcerates (confinement can be as a result of the presence of electrostatic potentials, semiconductor surface, an interface between different semiconductor materials) the motion of conduction band electrons, valence band holes, or excitons (bound pairs of conduction band electrons and valence band holes) in all three spatial directions. A crucial way forward in quantum computation was the realization of a dot in GaAs [9]. In GaAs quantum dots, electron spins are used as qubits. The qubits are formed in a standard two-dimensional electron gas (2DEG) obtained at the interface of a GaAs/AlGaAs heterostructure. For

realization of well-defined spin qubits, the model equation for the on-site (U) and nearest-neighbor (U_{12}) Coulomb repulsion, respectively in a magnetic field is given by the Hamiltonian

$$H = H_0 + V_m = \frac{1}{2} \sum_i U N_i (N_i - 1) + U_{12} N_1 N_2 - e \sum V_i N_i + \sum_{i,k} \epsilon_{ik} n_{ik} - \vec{\mu} \cdot \vec{B}, \quad (2)$$

where H_0 is the unperturbed Hamiltonian [10] and V_m is correction to H_0 which results from magnetic fields and spin-couplings. $\vec{\mu} = g\mu_B \sum_m S_m$ is the magnetic moment with μ_B being the Bohr magneton. The m -th electron's spin-1/2 in the double dot is denoted by S_m . g is the Landae g -factor and $N_i = \sum_k n_{ik}$ counts the total number of electrons in dot i with $n_{ik} = \sum_{\sigma} d_{ik\sigma}^{\dagger} d_{ik\sigma}$. $d_{ik\sigma}$ annihilates an electron on dot i , in orbital k with spin σ . ϵ_{ik} denotes the energy of single-particle orbital level in dot, which yields the typical orbital level spacing $\epsilon_{ik+1} - \epsilon_{ik} \approx \hbar\omega_0$.

With a sufficiently large magnetic field intensity, a system of qubit can be initialized. Xu et al. [11] initialized a spin state with a singly charged InAs-GaAs quantum dot by optical cooling with near unity efficiency. The experiment requires magnetic field of 0.88 T in Voigt geometry and temperature of 5-0.06K. The details can be read in ref. [11]. Very recently Mar et al. [12] demonstrated that without the need of magnetic field, the initialization of a single quantum-dot hole spin with high fidelity (lower bound $> 97\%$), on picosecond time scales could as well be realized. The spin configuration has relevant eigenstates corresponding to $|\uparrow\downarrow\rangle$ or $|\downarrow\uparrow\rangle$

By occupying each dot with exactly one electron, the spin qubits are realized. Generally speaking, there are many systems that could be employed as qubits in a quantum computation such as the polarization of a single photon (the two states are vertical polarization and horizontal polarization). In this work, we demonstrate a quantum teleportation protocol by utilizing the spins of electrons confined in GaAs quantum dots. The teleportation is carried out using three GaAs quantum dots (say \mathcal{PP}' , \mathcal{QQ}' , \mathcal{RR}') and three electrons. The electron spin on GaAs quantum dot \mathcal{PP}' is used to encode the unknown qubit. The GaAs quantum dots \mathcal{QQ}' and \mathcal{RR}' combine to form an entangled state. We perform a Bell measurement and depending on the outcome of the measurement, a suitable Hamiltonian for quantum gate can be used to transform the spin-base information to charge-base information.

2 Demonstration of quantum teleportation in quantum dot

Now, let there be two participants, spatially separated in different sites in a quantum network, customarily called Alice and Bob. The qubit Alice at site P wishes to teleport to Bob in site R , has been obtained in a standard 2DEG formed at the interface of a GaAs/AlGaAs heterostructure, and is denoted by $|\xi\rangle_{\mathcal{PP}'} = \alpha|\uparrow\uparrow\rangle + \beta|\uparrow\downarrow\rangle$, where α and β are complex and satisfy the relation $|\alpha|^2 + |\beta|^2 = 1$. The entangled state of \mathcal{Q} and \mathcal{R} can be written in occupation number basis $|n_{\mathcal{Q}} \uparrow n_{\mathcal{Q}'} \downarrow n_{\mathcal{R}} \uparrow n_{\mathcal{R}'} \downarrow\rangle$

$$|\chi\rangle_{\mathcal{QQ}'\mathcal{RR}'} = \frac{1}{2} (|0001\rangle + |0100\rangle + |1011\rangle + |1110\rangle). \quad (3)$$

Qubits pair ($\mathcal{Q}\mathcal{Q}'$) belong to Alice while ($\mathcal{R}\mathcal{R}'$) belong to Bob. It can be deduced from equation (3) that, there are four possible states in $\mathcal{Q}\mathcal{Q}'$ which correspond to each state in $\mathcal{R}\mathcal{R}'$, i.e. ($|00\rangle \Leftrightarrow |01\rangle$, $|01\rangle \Leftrightarrow |00\rangle$, $|10\rangle \Leftrightarrow |11\rangle$ and $|11\rangle \Leftrightarrow |10\rangle$). The combined state of the qubits becomes $|\Phi^{(0)}\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = |\xi\rangle_{\mathcal{P}\mathcal{P}'} |\chi\rangle_{\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'}$. For Alice to achieve her aim, she performs a Bell state measurement on her qubits pair ($\mathcal{P}\mathcal{Q}$) to obtain the states of other qubits as

$${}_{\mathcal{P}\mathcal{Q}}\langle\Phi^\pm|\chi\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = \frac{1}{2\sqrt{2}} [\pm^{(1)}\alpha(|0011\rangle + |0110\rangle) + \beta(|1001\rangle + |1100\rangle)] = |\Phi^{(1a)}\rangle_{\mathcal{P}'\mathcal{Q}'\mathcal{R}\mathcal{R}'}, \quad (4a)$$

$${}_{\mathcal{P}\mathcal{Q}}\langle\Psi^\pm|\chi\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = \frac{1}{2\sqrt{2}} [\pm^{(1)}\alpha(|0001\rangle + |0100\rangle) + \beta(|1011\rangle + |1110\rangle)] = |\Phi^{(1b)}\rangle_{\mathcal{P}'\mathcal{Q}'\mathcal{R}\mathcal{R}'}, \quad (4b)$$

and then on qubit pair ($\mathcal{P}'\mathcal{Q}'$). Thus, the states of qubits pair ($\mathcal{R}\mathcal{R}'$) become

$${}_{\mathcal{P}'\mathcal{Q}'}\langle\Phi^\pm|{}_{\mathcal{P}\mathcal{Q}}\langle\Phi^\pm|\chi\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = \frac{1}{4} [\pm^{(1)}\alpha|\downarrow\downarrow\rangle \pm^{(2)}\beta|\uparrow\uparrow\rangle] = |\Phi^{(2a)}\rangle_{\mathcal{R}\mathcal{R}'}, \quad (5a)$$

$${}_{\mathcal{P}'\mathcal{Q}'}\langle\Psi^\pm|{}_{\mathcal{P}\mathcal{Q}}\langle\Phi^\pm|\chi\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = \frac{1}{4} [\pm^{(1)}\alpha|\downarrow\uparrow\rangle \pm^{(2)}\beta|\uparrow\downarrow\rangle] = |\Phi^{(2b)}\rangle_{\mathcal{R}\mathcal{R}'}, \quad (5b)$$

$${}_{\mathcal{P}'\mathcal{Q}'}\langle\Phi^\pm|{}_{\mathcal{P}\mathcal{Q}}\langle\Psi^\pm|\chi\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = \frac{1}{4} [\pm^{(1)}\alpha|\uparrow\downarrow\rangle \pm^{(2)}\beta|\downarrow\uparrow\rangle] = |\Phi^{(2c)}\rangle_{\mathcal{R}\mathcal{R}'}, \quad (5c)$$

$${}_{\mathcal{P}'\mathcal{Q}'}\langle\Psi^\pm|{}_{\mathcal{P}\mathcal{Q}}\langle\Psi^\pm|\chi\rangle_{\mathcal{P}\mathcal{P}'\mathcal{Q}\mathcal{Q}'\mathcal{R}\mathcal{R}'} = \frac{1}{4} [\pm^{(1)}\alpha|\uparrow\uparrow\rangle \pm^{(2)}\beta|\downarrow\downarrow\rangle] = |\Phi^{(2d)}\rangle_{\mathcal{R}\mathcal{R}'}, \quad (5d)$$

Table 1: Alice's results, the corresponding state obtained by Bob and the appropriate unitary transformation utilized by Bob to reconstruct the original state of the qubits. We have ignored the normalization for convenience

Alice's result	State obtained by Bob	Unitary transformation
$ \Phi^+\rangle \Phi^+\rangle$	$\alpha \downarrow\downarrow\rangle + \beta \uparrow\uparrow\rangle$	$(\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\downarrow + \downarrow\rangle\langle\uparrow)$
$ \Phi^-\rangle \Phi^+\rangle$	$-\alpha \downarrow\downarrow\rangle + \beta \uparrow\uparrow\rangle$	$(\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\downarrow + \downarrow\rangle\langle\uparrow)$
$ \Phi^+\rangle \Phi^-\rangle$	$\alpha \downarrow\downarrow\rangle - \beta \uparrow\uparrow\rangle$	$(\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow) \otimes (\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow)$
$ \Phi^-\rangle \Phi^-\rangle$	$-\alpha \downarrow\downarrow\rangle - \beta \uparrow\uparrow\rangle$	$(\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow) \otimes (\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow)$
$ \Psi^+\rangle \Phi^+\rangle$	$\alpha \downarrow\uparrow\rangle + \beta \uparrow\downarrow\rangle$	$(\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow)$
$ \Psi^-\rangle \Phi^+\rangle$	$-\alpha \downarrow\uparrow\rangle + \beta \uparrow\downarrow\rangle$	$(\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow)$
$ \Psi^+\rangle \Phi^-\rangle$	$\alpha \downarrow\uparrow\rangle - \beta \uparrow\downarrow\rangle$	$(\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow)$
$ \Psi^-\rangle \Phi^-\rangle$	$-\alpha \downarrow\uparrow\rangle - \beta \uparrow\downarrow\rangle$	$(\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow)$
$ \Phi^+\rangle \Psi^+\rangle$	$\alpha \uparrow\downarrow\rangle + \beta \downarrow\uparrow\rangle$	$-(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow)$
$ \Phi^-\rangle \Psi^+\rangle$	$-\alpha \uparrow\downarrow\rangle + \beta \downarrow\uparrow\rangle$	$(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\downarrow + \downarrow\rangle\langle\uparrow)$
$ \Phi^+\rangle \Psi^-\rangle$	$\alpha \uparrow\downarrow\rangle - \beta \downarrow\uparrow\rangle$	$-(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\downarrow + \downarrow\rangle\langle\uparrow)$
$ \Phi^-\rangle \Psi^-\rangle$	$-\alpha \uparrow\downarrow\rangle - \beta \downarrow\uparrow\rangle$	$(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow)$
$ \Psi^+\rangle \Psi^+\rangle$	$\alpha \uparrow\uparrow\rangle + \beta \downarrow\downarrow\rangle$	$-(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow)$
$ \Psi^-\rangle \Psi^+\rangle$	$-\alpha \uparrow\uparrow\rangle + \beta \downarrow\downarrow\rangle$	$(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow)$
$ \Psi^+\rangle \Psi^-\rangle$	$\alpha \uparrow\uparrow\rangle - \beta \downarrow\downarrow\rangle$	$-(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow + \downarrow\rangle\langle\downarrow)$
$ \Psi^-\rangle \Psi^-\rangle$	$-\alpha \uparrow\uparrow\rangle - \beta \downarrow\downarrow\rangle$	$(\downarrow\rangle\langle\uparrow - \uparrow\rangle\langle\downarrow) \otimes (\uparrow\rangle\langle\uparrow - \downarrow\rangle\langle\downarrow)$

where we have denoted the four Bell states by $|\Phi^\pm\rangle = 2^{-1/2}(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle)$ and $|\Psi^\pm\rangle = 2^{-1/2}(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle)$. The $\pm^{(1)}$ and $\pm^{(2)}$ represent the results corresponding to BSM on qubit pair $(\mathcal{P}, \mathcal{Q})$ and $(\mathcal{P}', \mathcal{Q}')$ respectively. The above states represent the 16 possible states which Alice's system will collapse into after the measurement. One can also observe that these states are pure entangled two-qubit states. Alice then communicates the results of the measurement to Bob, that can choose an apt unitary transformation via zero electron occupation and double electron occupation as basis in order to completely recover $|\xi\rangle_{\mathcal{P}\mathcal{P}'}$ on site R . Thus, The spin-based information can undergo a transformation to charge based information via a proper Hamiltonian for the quantum gate. Moreover, the content of the information is unaffected. A more explicit expression for equations (5a-5d) and the appropriate unitary transformation which Bob could utilize in reconstructing the original state, are shown in Table 1. This process is also illustrated in Figure 1.

It is worth mentioning that because of the nonlinearity of interactions which is involved in the model, the only obstacle which could incapacitate our Bell measurement from reaching 100% of success probability is noise. Noise may set in while Alice performs the Bell measurement and Bob perform the unitary operation. This might be due to an imperfection of local operation. The properties of teleportation through noisy quantum channels can be measured by the fidelity². The most significant example of a noise channel is a depolarizing channel, which is known to introduce white noise. The depolarizing channel transforms a qubit $|\xi\rangle\langle\xi| \rightarrow \mathcal{R}_0 |\xi\rangle\langle\xi| + (1 - \mathcal{R}_0)I \otimes I/d$, where parameter d denotes the dimension of the quantum system. Parameter \mathcal{R}_0 ($0 \leq \mathcal{R} \leq 1$) is the reliability of the channel. A very noisy channel corresponds to $\mathcal{R}_0 = 0$.

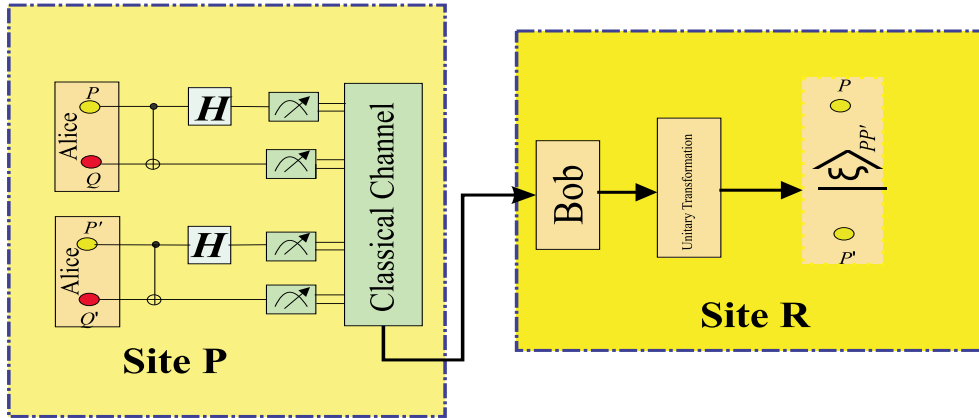


Figure 1: Schematic representation of quantum teleportation protocol of qubits formed in a two-dimensional electron gas formed at the interface of a GaAs heterostructure. The meters M_1 and M_2 represent the measurement. The particles a , b , 1 and 6 belongs to Alice, while particles 2 and 3 belongs to Bob and Particles 4 and 5 to Chika. H is the Hadamard gate. The double lines coming out of the meters carry classical bits (single lines denote qubits). Alice performs Bell state measurement on her qubit pairs $(\mathcal{P}, \mathcal{Q})$ and $(\mathcal{P}', \mathcal{Q}')$. Alice communicates the results of her measurement to Bob via classical channel. With information received from from Alice, Bob can recover the original state of the qubit (also in the same color combo) via an appropriate unitary transformation at site R .

²measures the overlap between a state to be teleported and the density operator for a teleported state.

3 Conclusion

In this paper, we have presented a model of quantum teleportation protocol by utilizing the spins of electrons confined in GaAs quantum dots to perform a teleportation. We have utilized three systems of electrons ($e^- = 3$). However, for $e^- > 3$, where on-site Coulomb repulsion approaches positive infinity, there will be no double occupation and the antiparallel configuration will be favored by the neighboring spin. Moreover, the teleportation of $n - e^-$ on n -sites is difficult and complicated but the same teleportation procedure described can be utilized. Suppose there are two- e^- on the n th-site, it then follows that there will be $(n - 2)$ - e^- on the $n - 1$ sites. Furthermore, if there is one spin-up electron on n th-site, then $n - 1$ sites will have a total spin of 1-spin up. All Alice needs to do is just to control the source qubit and the first $n - 1$ sites.

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